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SENSORS FOR THE DETECTION OF LAND-BASED MUNITIONS

by

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13. ABSTRACT

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Sensors for the Detection of Land-Based Munitions

I. Introduction.

There is a serious problem facing both third world and developed nations around the globe. This problem affects the use of land for agriculture, transportation and housing. It is encountered in any place where wars have been fought, or ordnance used, in the last 100 years. The problem is one of unexploded ordnance. The ability of unexploded ordnance to disrupt peaceful use of land (and water) resources is enormous. The effects of unexploded ordnance are only currently being realized. For instance:

-The United Nations estimates that there are more than 100 million land mines currently placed in regional conflicts throughout the world. Effective, deadly, easy to use and cheap (prices currently in the range of 3-5 dollars apiece) popularity of landmine warfare is increasing.
In contrast, clearance of mines by trained personnel is estimated to cost $200 each, resulting in a growing inventory of mines in use. [Walker, 1995]

- Following the end of the Cold War, Congress has begun to take inventory of many former test and training ranges, with the idea of eventually returning them to peaceful use. The problem of locating, and then disposing of, the myriad forms of unexploded ordance located on these ranges, (and in unmarked locations on many bases) must be solved.

- Throughout the world, people continue to find remnants of ordnance left from previous conflicts. This ordnance is still "live" in a surprising number of cases. WWII ordnance, alone, has presented range clearance problems, within the last five years, in locations as varied as Guam, Hawaii and San Diego.

- Finally, current technology allows the placement of hundreds of submunitions by a single 1000 pound bomb package. Detection and disposal of these munitions during peacetime range clearance, and following actual battles must also be addressed.

The task of dealing with the practical aspects of removing fired or armed ordnance belongs to the military's Explosive Ordnance Disposal (EOD) technicians, who are supported by the EOD Techinical Division, Indian Head, Maryland. It is there that the equipment and procedures which will be used by the EOD technician to detect, identify, recover and dispose of unexploded ordnance are developed. The scope of this undertaking is enormous, as the plethora of weaponry developed by countries around the world for use in all environs is difficult to imagine.

In this paper we will concentrate on just one specific tasking-a survey of the sensors which can be used in the detection of land based munitions. This effort is, in itself, a significant undertaking, given the recent advances in sensor manufacturing, particularly microprocessor technology used in data processing.

II Historical Perspective.

The detection of submunitions, landmines, bombs, projectiles and various other land-based munitions has been historically accomplished by trained personnel employed in some type of sweep scenario.

Surface ordnance was ordinarily easily detected visually, although in many areas, plant growth posed such difficulties that controlled burns were used to increase probability of detection. The time consuming process of lining up sweep troops, under the supervision of EOD technicians, and conducting large scale area clearance on foot, is still used frequently.

The problem of detecting buried, or hidden, munitions is another matter entirely. Prior to electronic metal detectors, buried bombs and projectiles were located by observing the geometry of entrance penetrations and "guessing" the location of their final resting place. The munition was then actually detected by digging to its location. The ability to accurately predict the behavior of an impinged bomb or projectile was not (and still is not) very good. Their behavior resulted in lots of earth being moved prior to location. Landmines were pursued in a more gentle fashion using probes and hand excavation by trained personnel (another method still used occasionally.)

With the advent of rudimentary magnetic detectors, large ferrous munitions could be located or localized for excavation. Lots of non-ordnance was still located, and cluttered up the scene, but excavation efforts were reduced. Within the last 20 years, additional advances produced metal detectors which were capable of sensing conductive metal of many types, and munitions of lesser size. All of these detectors were essentially man-carried and had corresponding slow clearance rates.

This brings us to present day and the current crop of new technology. These devices are capable of using all manner of physical properties and scientific advances. They can often be used on a variety of platforms including aircraft, vehicles, as well as being man-carried. These attributes are important because, just as the sensors for ordnance hunting have improved, so has the ordnance, itself. Sensitivities have been increased, firing mechanisms are more advanced and materials used in their construction include much less ferrous metal than in the past.

III. Sensor Overview

In order to make an intelligent decision concerning the possible use of a specific sensor for a particular problem, it is essential that the theory of operation of the sensor, its limitations, and the conditions which might affect its performance, are fully understood. In conducting this overview of sensor technology we have divided the sensor types into six major categories based upon the principle of their operation. These major categories are: electromagnetic, conductive/resistive, mechanical, optical, acoustic, and chemical. Examining each of these categories, separately, we will discuss the theory behind the operation of each individual sensor types and then later address specific systems which use them.

At this point it is prudent to inject one additional note concerning sensors and their use. Many manufacturers and contractors are currently using improvements in microprocessor design to incorporate a number of sensor types into a single detection system. These suites of hybridized sensors are, in general, superior to a single sensor arrangement. There is an inherent difficulty, however, in attempting to survey and classify the effectiveness of the myriad combinations of sensor packages which may be derived in this fashion. The end effectiveness of these systems is determined, in large part, by the treatment of the sensor data and evaluation by trained users. For this reason, the scope of this paper will be limited to single sensor systems, which are defined as requisite sense heads/arrays and the electronics which support the conversion of sensor data to indicate ordnance presence.

IV Electromagnetic Sensors

This sensor category uses some form of electromagnetic property or energy in order to function.

1. Electromagnetic Field

Theory- The earth's magnetic field is generally constant within a local area, with a strength of approximately .5 gauss (1 gauss= 100,000 gamma 1 Tesla=10,000 gauss.) The majority of the field is derived from variation in spin rates between the earth's core and mantle. It can be roughly represented by a large dipole which passes through the earth's center and is about 11 degrees displaced from the earth's axis of rotation. A magnetometer is a sensor which is designed to measure this field. There are two main variations among magnetometers. These are total field magnetometers and vector magnetometers. The first is a non-directional device which produces an output which is a function only of the total magnetic field passing through the device. The latter measures only the component of the magnetic field which lies parallel to their sensitive axis. Total field magnetometers include proton precession and optically pumped magnetometers. Vector magnetometers include flux gate, Hall effect and magnetorestrictive magnetometers. [Fraden, 1993]

a. proton precession-uses fluid (usually water) which is placed in a container within a solenoid, the axis of which is aligned at right angles to the magnetic field under investigation. A polarizing field is developed when the solenoid is energized. This aligns the magnetic spin axis of the water's protons perpendicular to that of magnetic field. When the polarizing field is instantaneously removed, the protons begin to precess about the axis of the magnetic field under investigation. A voltage, proportional to the magnetic field strength, is induced in the solenoid. This voltage can be amplified and measured. Capable of 10 readings per second with resolution to .1 nanoTesla. [Bartington, 1994] pros: very sensitive, is used as the common calibration standard. Can be ganged for use as a gradiometer which is well suited to airborne platforms.

cons: somewhat slow (Overhauser effect used to improve response speeds), large size and power, useful only with ferrous metals.

b. optically pumped-light from a cesium metal vapor lamp is circularly polarized and directed along the approximate axis of the magnetic field to be measured. Light passes through an absorption cell containing vapor of the same metal. The intensity of the emerging beam is monitored using a photocell. Its intensity is indirectly proportional to magnetic field strength. (Zeeman splitting phenomena) [Bartington, 1994]

Pros: very sensitive-10 pico Tesla, fairly rugged.

Cons: Large power requirements. must be aligned within 45 degrees of magnetic field or multiple sensors ganged to provide coverage. Limited life of approximately ten years.

c. flux gate. - These magnetometers use a specific property of magnetic flux to determine the local field strength. By using an exciting coil to drive a highly permeable metal core in and out of a condition of saturation (using a square voltage waveform of sufficient magnitude,) magnetic flux lines in the core area are pulled into or out of the core. At saturation, the core inductance falls rapidly and current levels spike to DC resistance limited levels. A separate sensing coil will detect these movements by the resultant induced current spikes and, using circuitry, compare their phase, polarity, and size, to that of the local "null" field used in calibration. Using two parallel toroidal cores with opposed excitation windings with a single overwound pickup coil produces cancellation of all but desired phase varying signals attributed to the external field. Output via a low pass filter is a DC or slowly varying voltage which reflects external field behavior. Currently the **most popular magnetometer design.**

Sensitivity: 12 mV/gauss

Pros: Accurate measurement of weak magnetic fields, small low power, relatively simple, robust circuitry and materials.

Cons: Useful only on ferrous metals at small ranges. [Fluxgate Magnetometry, 1991]

d. Hall effect. - This sensor is based upon the fact that a moving electric carrier (electron) will experience a force produced by a magnetic field which intersects its path of travel. Using a thin strip of metal through which a current is passed in the longitudinal direction, voltage readings are established in the same plane, but at a perpendicular. As the strip is passed through magnetic fields, and lines of flux pass orthogonally through the strip, electrons are displaced toward one side of the strip. The resultant voltage potential between sides of the strip relate the strength of the magnetic field. [Fraden, 1993]

Pros: Simple, rugged, established method, .

Cons: Relatively large voltages required. Limted to use with ferrous metal targets.

e. Magnetorestrictive.

Theory- Some materials have been found to vary in their resistance to electric current as the strength of the magnetic field in which they are located varies. Using two magnetoresistors, having this property, in opposing Wheatstone bridge configuration, along with two shielded magnetoresistors will yield a circuit which provides voltage output based upon magnetic field strength changes. [Brown, 1995]

Sensitivity: 10^-6 gauss (2.5 mV/gauss)

Pros: small, sensitive, low power

Cons: ferrous metals only, relatively new technology

2. Inductance

Theory- The term inductance implies the magnetic flux coupling of two coils, one of which provides the driving field. In common use, the inductance sensor uses a reference coil to produce a magnetic field which in turn induces eddy currents in any conductive material through which it passes. Two pickup methods may be used. In the first, a second sensing coil detects the presence of magnetic fields that result from the induced eddy currents in the targets. In the second, the sensor is a tuned circuit which uses AC voltage driven at a frequency based upon an LC characteristics inherent within the device. When the circuit is disrupted by increased mutual inductance from a target, the circuit voltage drops, providing an indication of target presence.

The sensor can detect most conductive substances, not just ferrous metals. Pulsed induction sensors have been in use since the 1970's for ocean salvage operations. There is a physical limitation inherent in the sensor detection range as range falls away at a rate of 1 /r^6 (r-radius of sensor coils.). [TR-311, 1993, McFee, 1984]

Pros: Robust systems capable of being fielded in small packages with low power requirments. Useful in detecting all conducting materials.

Cons: Relatively short range, will not detect plastics.

3. Ground Penetrating Radar (GPR)

Theory- Electromagnetic radiation is emmitted into the ground where it may be absorbed or reflected from a target surface. The characteristic of the reflected signal is dependent upon the radar signal used, soil dielectric constant (which is in turn dependent upon soil makeup and moisture), and the material which makes up the target. Smooth surfaced metallic targets reflect energy most efficiently. Microprocessing of target returns, time of signal flight, phase polarization, amplitude time delay and propagation direction, yields information on target type and location. All GPR systems are limited by high moisture content in soils, reliance on metalllic or air/plastic interfaces which must provide sufficient return for detection, and energy loss at the air/surface interface. Four categories of GPR, based upon transmission characteristics, have been established. Large bandwidth, pulse radars are currently popular. Microprocessor use in synthetic aperture processing into plan or 3-D images is an important detail in reducing current high false positive rate. Resolution: at high frequencies (of approximately 1 GHz) depth resolution in the 1-3 centimeter range is possible. Poor angular resolution of approximately 60 degree arcs results unless synthetic aperture techniques are applied. **Soil type is probably the over-riding variable in any GPR performance .** [TR-311, 1993, Herman, 1994]

a. short pulse radar Frequency band: 30 Mhz to 2 Ghz

Pros: High frequency results in good depth resolution

Cons: Limited to short range use.

b. video pulse radars. Frequency band: dc to 3 Ghz .

Pros: large bandwidth provides good target information with minimal signal interference.

Cons: Difficult to separate/interpret large variety of frequency returns.

c. Step frequency radar: uses continuous wave radar, stepped in frequency based upon the phase return of relected waves.

Pros: Effectively selects low vs. high frequency transmissions to optimize resolution and penetration.

Cons: Lacks depth of penetration, best suited for shallow use.

d. frequency modulated continuous wave radar: single/discrete number of operating frequencies.

Pros: Using synthetic aperture techniques/microprocessing provides excellent holographic images.

Cons: Very sensitive to changes in soil conductivity and height of antennae above ground. Somehwat slow. Requires large processing abilities.

4. X-ray Backscatter.

Theory-pulsed x-ray radiation is directed into the soil where it can impinge upon targets and can be reflected back to a receiver. Backscatter levels obtained from a clean area are compared to that received from the sweep area to determine target presence. The key issue involved here is that the electron density of a material affects its ability to scatter x-ray radiation. Plastics generally have low atomic numbers and are good scatterers. Difference in scattering properties between plastic and soil provide the contrast required to image (Compton Backscatter Imaging.) [TR-311, 1993, Keshavmurthy, 1995]

Pros: high frequencies results in good target resolution, works on plastic.

Cons: High energy use; high frequencies result in shallow detection ranges.

Note: Additional work is being done with x-rays to ascertain feasibility of fluorescence or emmission of other energy in sufficient levels to allow detection, following concentrated x-ray irradiation of plastic explosives.

V. Conductivity/resistivity.

Theory- Using a system of portable transmitter and receivers an area of ground can be surveyed for variation in its ability to conduct current. By using an exciting field to induce eddy currents in the soil, measurements of the eddy current magnetic field will provide an indication of the soils conductivity. By establishing a baseline standard in a clean area prior to searching, changes in conductivity in the soil which may result from conducting substances such as mines can be detected. The system does not target specific mines but plots gradations in soil resistivity. A typical dual coil system with 3.7 meter coil separation provides 6m penetration.

Pros: reasonable soil penetration depth, possible plastic mine applications

Cons: horizontal range is limited, natural variation in soil conductivity in search area must be accounted for by recalibration. Image resolution is poor, targeting individual mines is not feasible. Capability rests more practically in establishing minefield boundaries. [TR-311]

VI. Mechanical

1. Tactile

Theory- The movement of a tactile sensor arm along the surface of man-made surfaces has been found to produce vibration patterns which reflect distinct resonant frequencies which vary from those produced by natural surfaces such as stone, wood, etc. By using a tactile probe connected to a piezoelectric device, vibrations produced by movement along a surface can be analyzed using Fast Fourier transforms to determine whether frequency patterns indicate possible man-made targets which may be munitions. This system can only be used on munitions which are not buried. It has no ability to discriminate between ordnance and non-ordnance targets, only providing information on whtether the object is man-made. Best incorporated into a sensor suite for use in robotic search/detection systems. [Mangolds, 1993]

Pros: Capable of detecting plastic or metal mines, simple and robust technology, easily adaptable to remote/autonomous operation.

Cons: Inability to discriminate effectively between ordnance and non-ordnance man-made targets.

VII. Optical

Theory- There are two basic categories within this sensor type: passive or active. The first utilizes naturally occurring optical wavelength energies, which it collects and processes to provide required sensor information. The second type system emits energy within these wavelengths and then processes the return signal to provide information.

1. Infrared -A passive system which collects information about the specific infrared spectrum which is emmitted by a surface. It passivley scans large areas in order to determine if variations in emmissivity/soil temperature are present and, additionally if regular, characteristic minefield patterns are present. It has been found that following the emplacement of landmines the disturbed soil will exhibit a different moisture content than nearby undisturbed soils. This moisture differential will lead to a varying infrared signature, which is particularly evident during times of large air/soil temperature differential (evening/morning.) [Keeler, 1995]

Pros: System is particularly well-suited to large scale survey by airborne platforms and incorporation with intelligent microprocessor programs that excel at discerning mining patterns.

Cons: System useful primarily for landmines, rather than individual or random detection. Limited by weather conditions and moisture content of soil.

2. Laser -Laser is a form of highly concentrated light which can be directed onto a surface at known geometries. Its reflection produces information concerning range, phase, and surface type. Laser use has been limted mainly to use in underwater systems such as Magic Lantern and LiDaR, although its application to airborne surface detection appears feasible.[Keeler 1995]

Pros: large area search potential

Cons: limited to surface ordnance, cannot penetrate soil to significant depth.

VIII. Acoustic

1. Ultrasound

Theory- Apply the technology which has already been developed for use in medical diagnosis to ordnance detection.. By directing high frequency acoustic energy from a transducer and measuring reflected energies an image can be produced.

Pros: Excellent resolution

Cons: Very short range due to high frequency attenuation in soils. [TR-311]

2. Seismic

Theory. By directing low frequency acoustic energy into the soil and then using a variety of arrays to detect reflected energies and variation in acoustic wave speed/direction it is possible to resolve buried structures. Paleontologists have been using variations of this technology in researching buried fossils for some years. The feasibility of making the technology portable, in order to cover larger areas of terrain are being pursued by Army researchers. Application involves a truck mounted device using a water column to produce the acoustic energy and towed receiver array.

Pros: Good range and penetration through dense, moist soils, non-magnetic capabilities.

Cons: Large, slow and low frequencies result in poor resolution. [TR-311]

IX. Chemical

These sensors use the chemical properties of the explosives found in ordnance to determine their presense.

1. Vapor Detection-

Theory- The presence, in almost all explosives, of some nitrate form, can be used as a key to determine ordnance presence. Assuming the presence of explosive contamination on the ordnance surface, or lack of hermetical seal to the ordnance case, it is possible to produce a sample of gas found in the buried ordnance airspace and heat the nitrate compounds found therein in the presence of a catalyst to produce nitrous oxide. This gas can then be measured and a direct correlation made to explosive presence. Another variation of this technique requires mixture of nitrous oxide with ozone and measure resulting chemoluminescence using photodetectors. [Patel 1995]

pros: applicable to almost all ordnance types, detects non-metallic ordnance.

cons: current technology required physical application of solvent to ordnance case, resulting in slow, dangerous process.

2. Bioluminescence

Theory- A bacteria which grows exclusively on the explosive known as trinitrotoluene (TNT) has been found. Because TNT is the basis for many common explosive mixtures, the use of this bacteria as an indicator has been researched. One specific enzyme produced by the bacteria, TNT reductase is combined with luciferase (a light emitting enzyme) and NADH to produce a light emmitting substance whose luminescence can be measured to determine explosive presence. The technique is still experimental. No sampling method has been devised. [Patel, 1995]

Sensitivity: Detection of 2X10^-14 molar solution of TNT achieved.

Pros: Applicable to any TNT based explosive, irrespective of mine case.

Cons: Slow, no adequate sample collection method

X. Definitions of Sensor Performance.

In order to quantify and compare the performance of sensors it is important to establish criteria which identifies the ability of the sensor to correctly perform its task. The ultimate sensor will be able to detect ordnance items, provide data on their exact location, while consistently rejecting other detected items that are not ordnance.

In a realistic sensor evaluation, such as the one carried out recently at Jefferson Proving Grounds, Indiana , an effort was made to statistically determine the efficacy of approximately 29 sensor systems. The first step of the evaluation involved establishing a baseline database for the search area where the evaluation was to be conducted. This database included the position and classification of every ordnance and non-ordnance object within the test area.

Each system demonstrator was required to search the area and then provide results which delineated the position of all objects found, and their classification as ordnance or non-ordnance.

Based upon an arbitrary critical radius of detection (rcrit), the two databases could be compared to provide the following information:

- Detected target set (E): Those targets for which the demonstrator declared positions were within the distance rcrit of their baseline positions.

-True Positive set (TP): the subset of the detected targets which were declared to be ordnance and, in fact, were.

-Mistyped Target set (MT): The subset of detected targets which were declared to be non-ordnance but were actually ordnance.

-True Negative set (TN): The subset of detected targets which were declared to be non-ordnance and, in fact, were.

-False Positive set (FP): The subset of detected targets which were declared to be ordnance, but were actually non-ordnance.

-False Negative set (FN): Those items which were detected and declared as ordnance, whose position did not correlate to any baseline objects.

-Negative False set (NF): Those items which were detected and declared as non-ordnance, but whose position did not correlate to any baseline object.

Undetected Ordnance set (UO): Those ordnance objects which were in the baseline database which were not detected by the system.

Undetected Non-ordnance set (UN): Those non-ordnance items which were in the baseline database which were not detected by the system.

This data could be used, in conjunction with known search area size (Area), number of total items placed (B), number of ordnance items placed (BO), number of non-ordnance items placed (BN), and time required for search, to establish a variety of significant parameters for each system's sensor performance.

The performance criteria selected included:

1. Detection Capability-four ratios which provide:

a. overall detection ratio- E/B, the overall ability to find all items. Large number desired.

b. ordnance detection ratio- (TP+MT)/BO, the ability to detect ordnance items, regardless of classification applied.

c. non-ordnance detection ratio- (TN+FP)/BN, the ability to detect non-ordnance items, without regards to misclassified items. (questionable value)

d. mistyped ordnance ratio- (MT)/(MT+TP), the ability to distinguish ordnance from non-ordnance. Low number desired (zero)

2. False Negative Rate-two ratios which provide:

a. false negative ratio- (FN)/(FN+TP), the ability to distinguish ordnance from false returns and clutter. Low score is good.

b. area false alarm ratio-(FN+NF)/area, a measure of false alarms (ie. no item of any type located at position.) A low number is good.

3. False Positive Rate-FP/(FP+TN), one ratio which measures the ability to classify detected items correctly.

4. Target Classification Capability- # of ordnance type detected and correctly classified/ number of ordnance type in baseline database. Example: number of projectiles detected, and correctly classified as such, divided by total number of projectiles present in the baseline database.

XI. Survey of Commercial Sensor Systems

Note: where available some indication of sensor performance in evaluation at Jefferson Proving Ground will be noted. Common performance characteristics which were determined at this 40 acre, mixed munition (bombs, projectiles, landmines, cluster munitions) will include:

Ordnance Detection Ratio (ODR)- the ratio of all ordnance items detected, even if misclassified over the number in a test field.

False Alarm Rate (FAR) - number of items detected which did not actually exist per unit area.

Manufacturer: Lawrence Livermore Laboratories

Sensor Type: GPR/ pulsed side-looking

Sensor characteristics: 400Mhz-1500Mhz, 3kv pulse

Platform: vehicle or airborne

Swath/depth/clearance rate: 10m./-/ Clearance rate dependent upon platform

Primary munition type/material/size detected: antitank mines, bombs/metallic/>30 cm

Sensor limitations: soil dielectric, moisture content affects performance.

Contact/Non-contact

Pros: 9 meter standoff, relatively fast clearance rates

Cons: Large power and data processing requirements. Soil characteristics must be matched for best performance.

Comments: GPR performance is heavily dependent upon soil types. [Sargis, 1995]

Manufacturer: Lawrence Livermore Laboratories

Sensor Type: Micropower Impulse radar

Sensor Characteristics: ultra-wide bandwidth,

Platform: Vehicle

Swath/depth/clearance rate: 2m^2 per /2-10 cm/-/

Primary munition type/material/size detected: antitank mines/metal or plastic/-/

Sensor limitations: high frequency band loss in some soils.

Contact/Non-contact

Pros: lower cost,power and weight than GPR. detects non-metallic objects.

Cons: Small stand-off for detection

Comments: Produces two or three-D tomographic images. Not ready for fielding just yet.

[Gavel, 1995]

Manufacturer: SRI

Sensor Type: GPR

Sensor characteristics: Synthetic aperture, pulsed radar

Platform: plane w/DGPS link

Swath/depth/clearance rate: /-/5ft/50sq kn per hr/

Primary munition type/material/size detected: bomb/metallic/large

Sensor limitations: GPR soil dependency, platform can only operate in fair weather to allow for smooth transit at low altitude.

ODR: .011

FAR: 1.95

Pros: fast clearance rates

Cons: In actual testing performance was very poor.

Comments: GPS adaptation to airborne platform not yet feasible. [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Geonex Aerodat

Model: Scintrex

Sensor Type: Cesium vapor optically pumped magnetometers

Sensor characteristics: Two cesium vapor magnetometers mounted at opposite ends of a 6-m kevlar tube towed beneath a helicopter.

Platform: helicopter w/DGPS link

Swath/depth/clearance rate: /-/5ft/50sq km per hr/

Primary munition type/material/size detected: bomb/metallic/large

Sensor limitations: Towed body affected by wind. Poor ability to correlate target detect to positional accuracy due to platform/ground dynamics.

ODR: .04

FAR: .95

Pros: fast clearance rates

Cons: In actual testing performance was very poor, with overall detection ratios less than 5 per cent. [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Foerster

Sensor Type:Magnetometer- Ferex MK 26

Sensor characteristics: N/A

Platform: man carried

Swath/depth/clearance rate: -/2-5 ft/4 acres per day

Primary munition type/material/size detected: Bombs/metals

Sensor limitations: metals only

ODR: .38

FAR: 3.2

Pros: small, rugged, lightweight, low power

Cons: relatively slow clearance rates, no classification ability, ineffective with plastic.

Comments: Currently one of Navy EOD tool sets [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Geometrics

Model- MagDis (prototype)

Sensor Type: Optically pumped cesium magnetometer

Sensor characteristics: 5 cesium magnetometer sensors mounted in array

Platform: man portable (towed)

Swath/depth/clearance rate: 10ft/ >6 ft/7 acres per day

Primary munition type/material/size detected: mortars and bombs/iron

Sensor limitations: iron only

ODR: .22

FAR: .43

Pros: classification capability

Cons: no plastic capability

Comments: Best performance for large deep targets. Processing accomplished via tether to trailing trailing ATV data processing module.[Institute for Defense Analysis ,Mar 1995]

Manufacturer: Georadar

Model: Georadar 1000A

Sensor Type: GPR

Sensor characteristics: stepped frequency modulated signal

Platform: manportable (towed two-wheeled array)

Swath/depth/clearance rate: -/5-10 ft/ .5 acre per day

Primary munition type/material/size detected: projectiles/metal

Sensor limitations: no classification capability

ODR: .05

FAR: .13

Pros: may work on plastic mines.

Cons: Difficulty in heavy wet clay soils, very slow.

Comments: preproduction model used in testing, poor performer. [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Australian Defense Industries

Model: GT-TM4

Sensor Type: optically pumped magnetometer

Sensor characteristics: N/A.

Platform: Man portable or towed

Swath/depth/clearance rate: 10/20 acres per day depending on platform

Primary munition type/material/size detected: bombs, mortars and projectiles/ferrous

Sensor limitations: ferrous metals only

ODR: .40

FAR: .43

Pros: good performance on large ferrous objects

Cons: no classification ability, ferrous only

Comments: During testing all metal objects with a mass of 100 gr or more were declared as ordnance. Man-portable operation requires two men. [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Chemrad

Model: 822l

Sensor Type: Optically pumped magnetometer

Sensor characteristics: N/A

Platform: man portable or surface towed

Swath/depth/clearance rate: 20 ft/-/10 acres per day

Primary munition type/material/size detected: bombs/ferrous

Sensor limitations: No plastic capability

ODR: .26

FAR: 1.9

Pros: fair performance against large ferrous objects

Cons: No classification ability, poor sensitivity

Comments: none [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Schonstedt

Model: MAC 51-B

Sensor Type: magnetic induction

Sensor characteristics: pulsed 82.5 kHz excitation frequency

Platform: man portable

Swath/depth/clearance rate: N/A

Primary munition type/material/size detected: Designed for pipe/cable detection

Sensor limitations: metallic objects only

Pros: rugged, low power, commercially available

Cons: not designed with ordnance in mind

Comments: no actual data available on performance in ordnance detection

Note: Data derived from manufacturer's information pamphlet

Manufacturer: Schonstedt

Sensor Type: Fluxgate magnetometer

Sensor characteristics: N/A

Platform: man-portable

Swath/depth/clearance rate: N/A

Primary munition type/material/size detected: bombs and projectiles/ferrous

Sensor limitations: detects only ferrous metals

ODR: N/A

FAR: N/A

Pros: small, lightweight, rugged, typical fluxgate magnetometer

Cons: lack of sensitivity, detects only ferrous metals

Comments: all-purpose magnetometer which can also be used for ordnance.

Note: Data derived form manufacturer's information pamphlet

References

Bartington, G., "Sensors for Low Level, Low Frequency Magnetic Fields", *Report for the IEE Colloqium 'Low Level Low Frequency Magnetic Fields'*, London, pp 2/1-9, 1994.

Daughton J. and Brown J., "GMR The Next Generation of Magnetic Sensors", Report prepared by Nonvolatile Electronics Inc. for Department of Transportation, DTRS-S7-94-C-00117, pp 2-9, Mar 1995.

Fraden, J., *AIP Handbook of Modern Sensors,* American Institute of Physics, pp 129-284, 1993.

Gavel, Mast, Warhus, and Azevedo, "AnImpulse Radar Array for Detecting Land Mines",in *Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium* , Monterey , pp 6/112-114, 1995

Grattan, K.V. , *Sensors-Technology Systems and Applications*, p. 248, IOP, 1991.

Herman H., Singh S., "First results in the Autonomous Retrieval of Buried Objects", *IEEE Proceedings* 1050-4729/94, pp2584-2587, 1994

Keeler, R. , "Electro Optics (Infra Red, LIDAR) Sensors", in *Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium* , Monterey pp 6-14-6-15, April 1995.

Keshavmurthy, S., "University of Florida Landmine Detection Project", report for the U.S. Army CECOM Night Vision and Electronic Sensors Directorate, 1995

Machler P. , "Detection Technologies for Anti-Personal Mines", in *Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium* , Monterey April 1995.

Mangold, A., "Lemmings- A Swarming Approach to Shallow Water Mine Field Clearance", Report No. MCR-R053-FM-9635-693, Prepared by Foster Miller Inc. for Defense Advanced Research Projects Agency, Arpa No. 5916, pp 4-7, Feb 1994.

McFee J., Chesney R., Das Y., Toews J., "Experimental Time Domain Electromagnetic Induction System", *Review of Scientific Instruments*, pp 968-973, Jun 1984.

Patel, D., "Best Type of Sensors for the Detection of Buried Mines", in *Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium* , Monterey April 1995.

Sargis P. , "Buried Mine Detection using Ground Penetrating Impulse Radar", in *Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium* , Monterey April 1995.

Walker J., "Moore's Law in the Minefield", in Proceedings from the Workshop on Anti-personnel Mine Detection and Removal, Lausanne, Switzerland, pp 1-3, June 1995.

NAVEODTECHCEN Technical Report TR-311, "Final Report-Technology Assessment for the Detection of Buried Metallic and Non-Metallic Cased Ordnance", Prepared by the Naval Explosive Ordnance Disposal Technology Center, pp 9-41, Jan 1993.

"Fluxgate Magnetometry", *Electronics World and Wireless World,* pp 726-729, Sep 1991.

Evaluation of Individual Demonstrator Perfromance at the Unexploded Ordnance Advanced Technology Demonstration Program at Jefferson Proving Ground (Phase I), (SFIM-AEC-ET-CR-95033), Institute for Defense Analysis, March 1995.

Survey of Collision Avoidance and Ranging Sensors, Rev 1, NAVEODTECHDIV Report, pp 3-7, Dec 1992

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